ATF Users Meeting
BNL | December 6th, 2017

Energy-chirp compensation in plasma — AE73

ATF experimental update

Richard D'Arcy

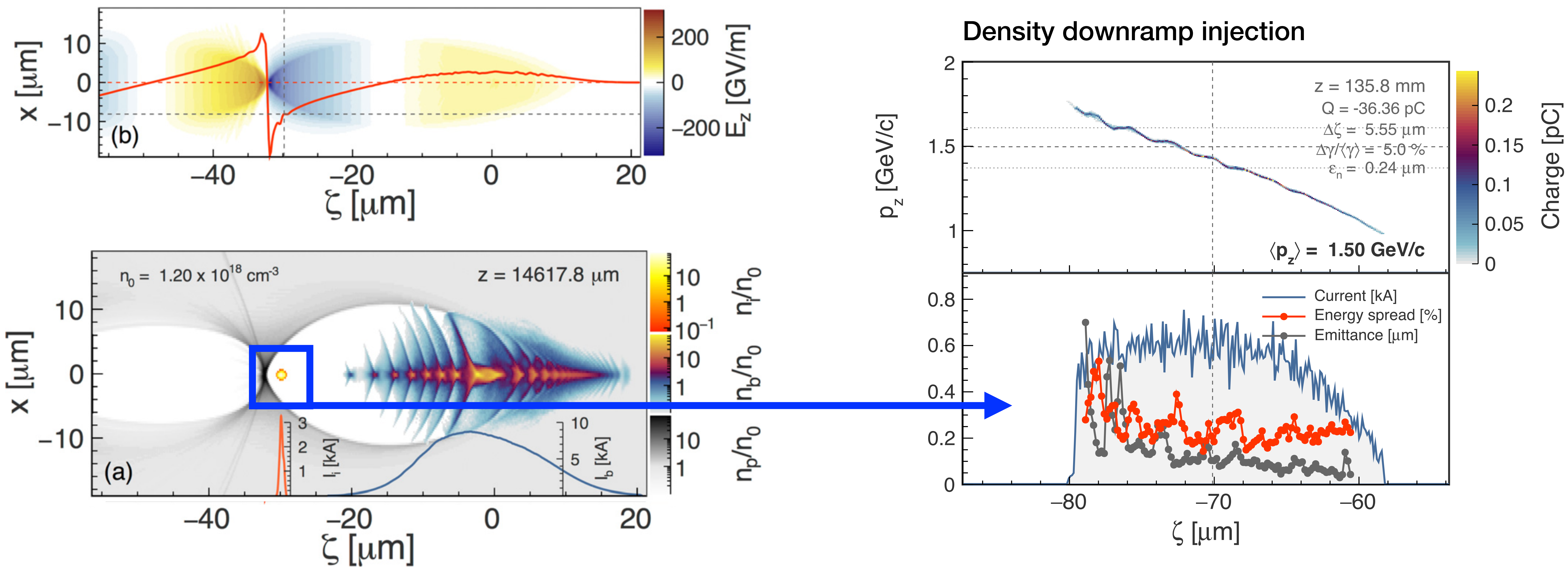
A. Aschikhin, S. Wesch, V. Wacker, J. Osterhoff and ATF staff members

FLASHFORWARD▸▸ Scientific Coordinator | Research Group for Plasma Wakefield Accelerators

Deutsches Elektronen-Synchrotron DESY, Particle Physics Division, Hamburg, Germany

Energy-chirp compensation in plasma

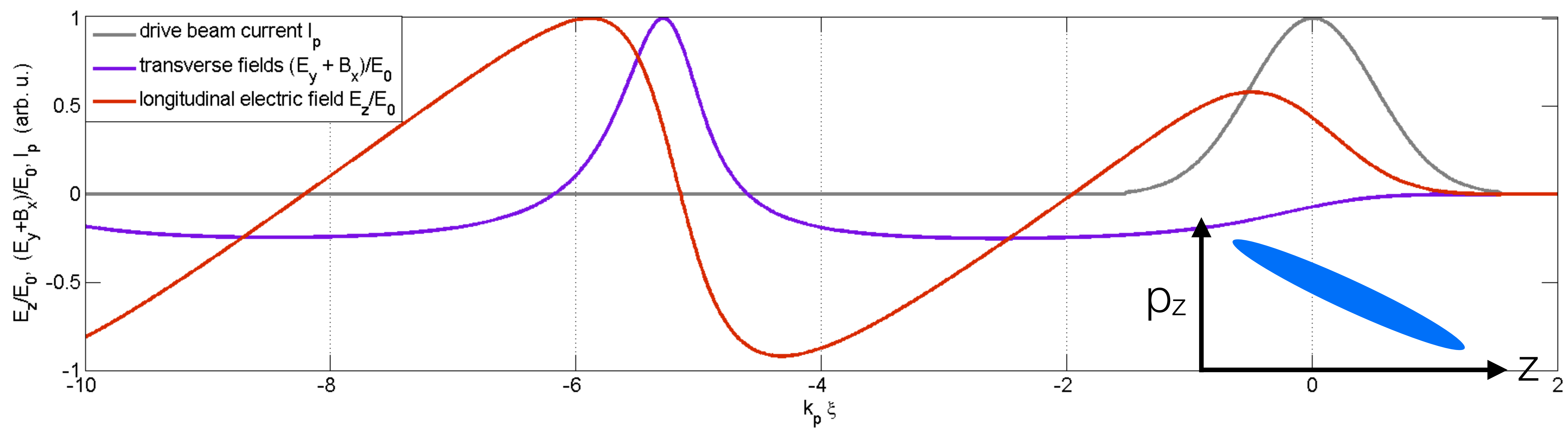
> Large negative chirps are characteristic for unloaded beam-driven PWFA accelerators



A. Martinez de la Ossa *et al.*, Phys. Rev. Lett. **111**, 245003 (2013)
A. Martinez de la Ossa *et al.*, Phys. Plasmas **22**, 093107 (2015)

Energy-chirp compensation in plasma

- Large negative chirps are characteristic for unloaded beam-driven PWFA accelerators
- Is it possible to utilise the wakefield slope and focussing properties generated by the beam itself driving a plasma wake?



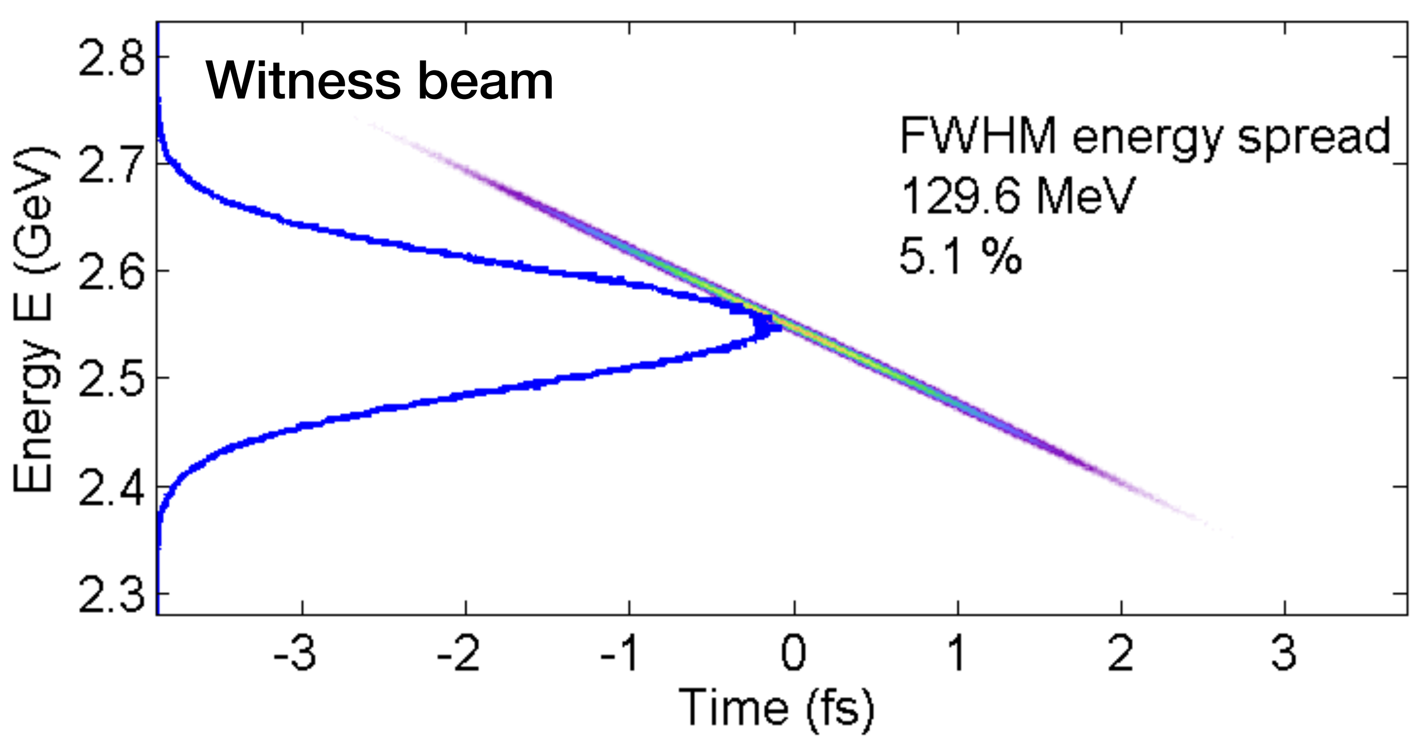
$$6 \cdot \sigma_z \lesssim \frac{\lambda_p}{4}$$

The full 6σ bunch length is required to fit inside the first quarter of the plasma wavelength

→ e.g. σ_t = 140 fs for $n_p = 10^{15}$ cm^{-3}

Energy-chirp compensation in plasma

- **Large negative chirps are characteristic for unloaded beam-driven PWFA accelerators**
- **Is it possible to utilise the wakefield slope and focussing properties generated by the beam itself driving a plasma wake?**



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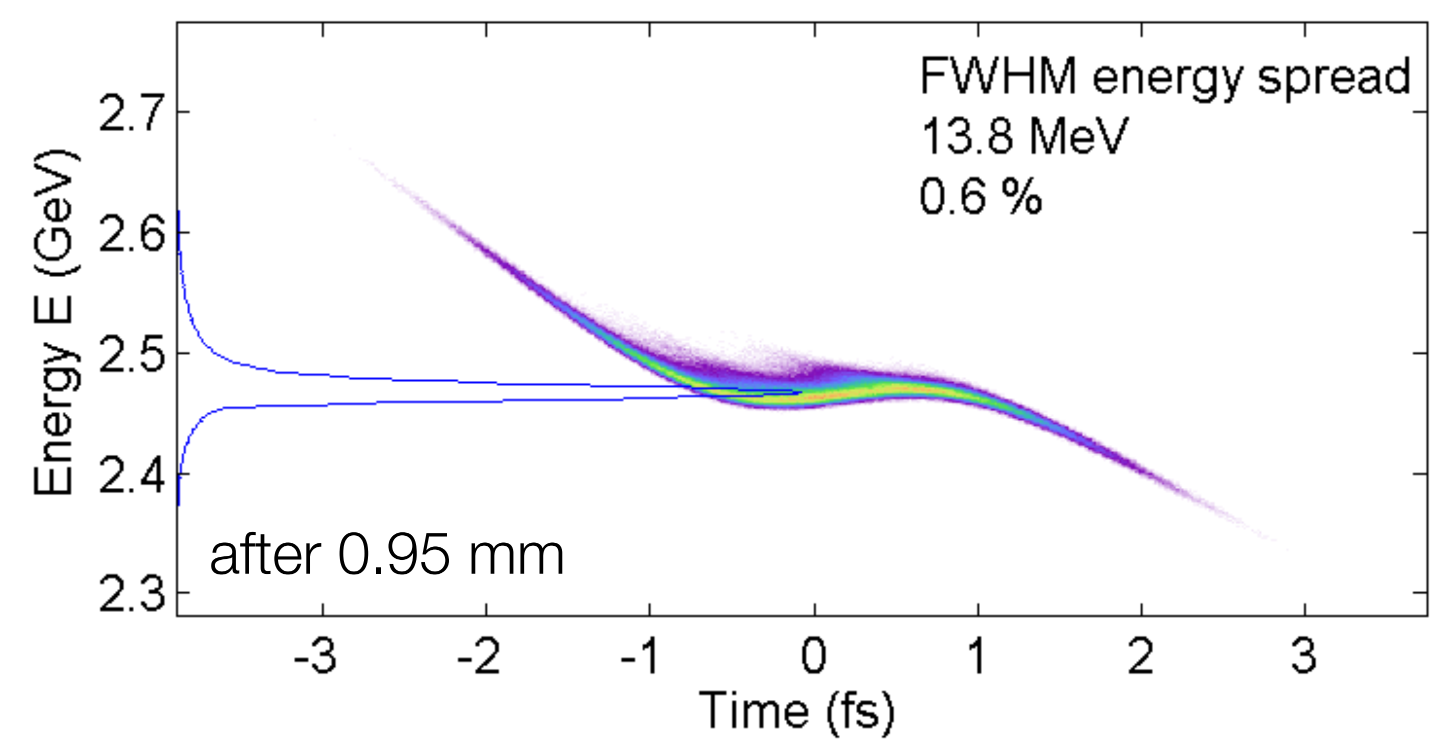
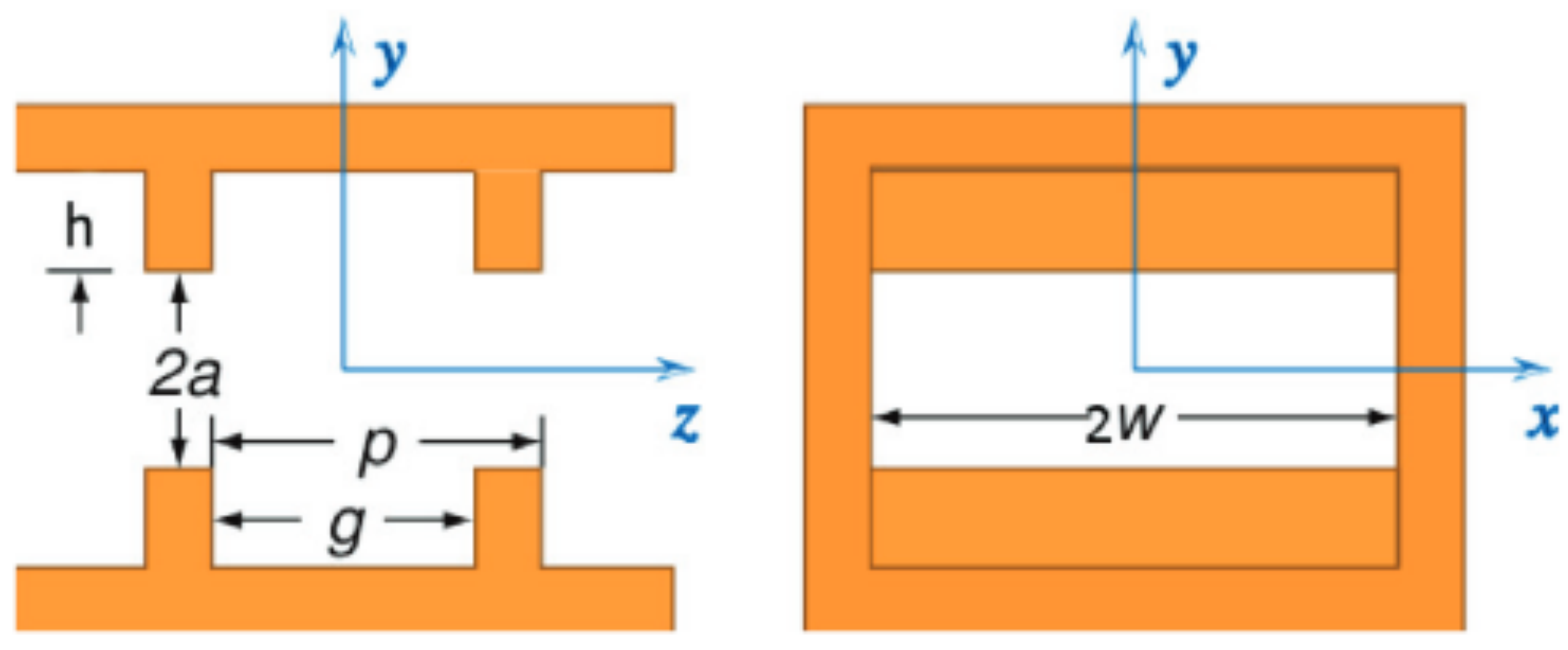


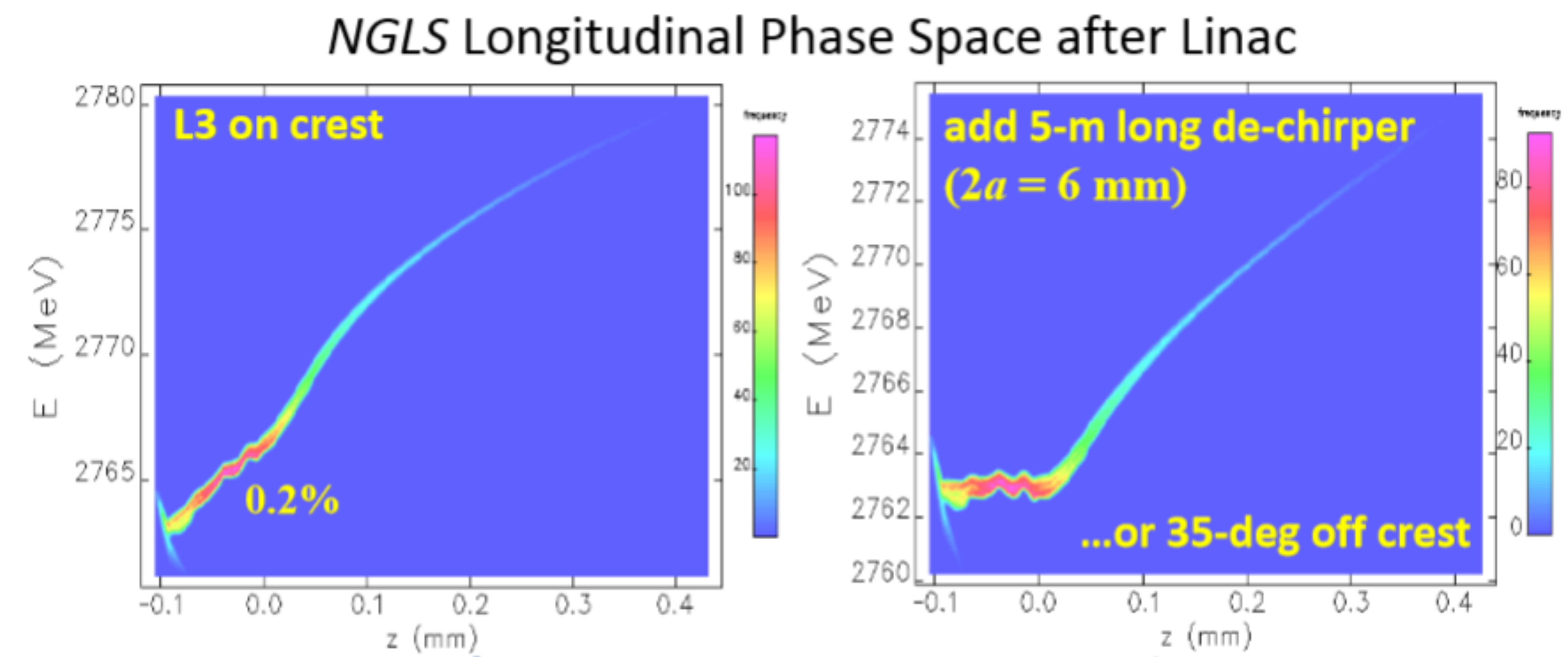
- Drive beam
  $\sigma_z = 7\ \mu m$, $\varepsilon_{x,y} = 1\ \mu m$, $I_B = 10$ kA,
  $Q = 574$ pC, $E = 1$ GeV
- Witness beam
  $\sigma_z = 0.23\ \mu m$, $\varepsilon_{x,y} = 10.3\ \mu m$, $I_B = 5$ kA,
  $Q = 32$ pC, $E = 2.5$ GeV

A longitudinal phase space diagnostic e.g. an RF deflector is necessary to confirm the negative chirp and quantify the de-chirping effect

Demonstrated wakefield-based beam dechirper techniques

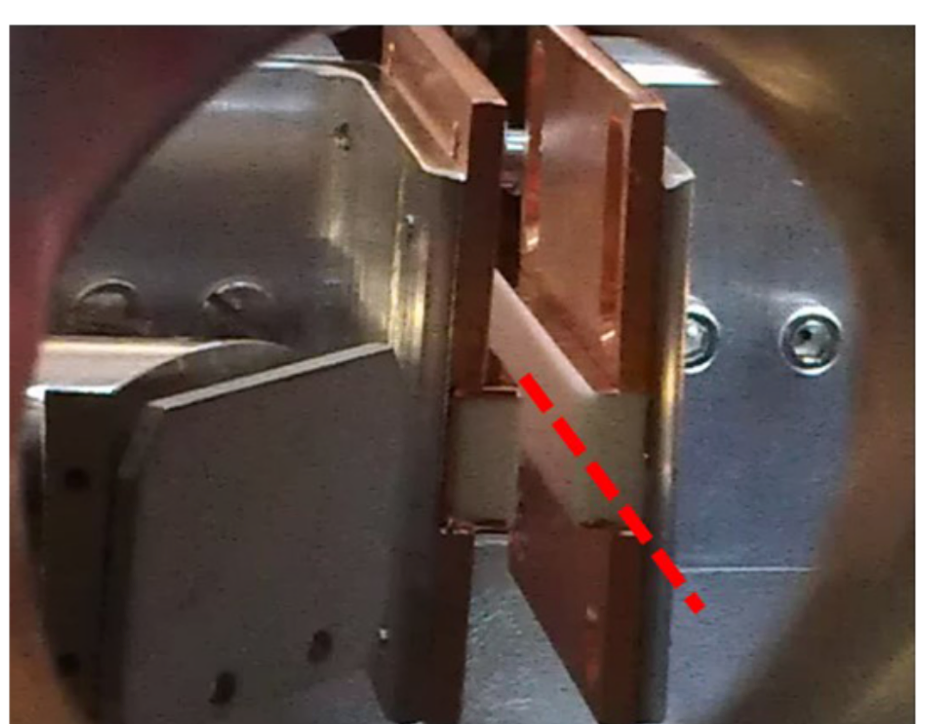
- Corrugated pipe beam dechirper - K.L.F. Bane, G. Stupakov, NIM A 690, 106 (2012)

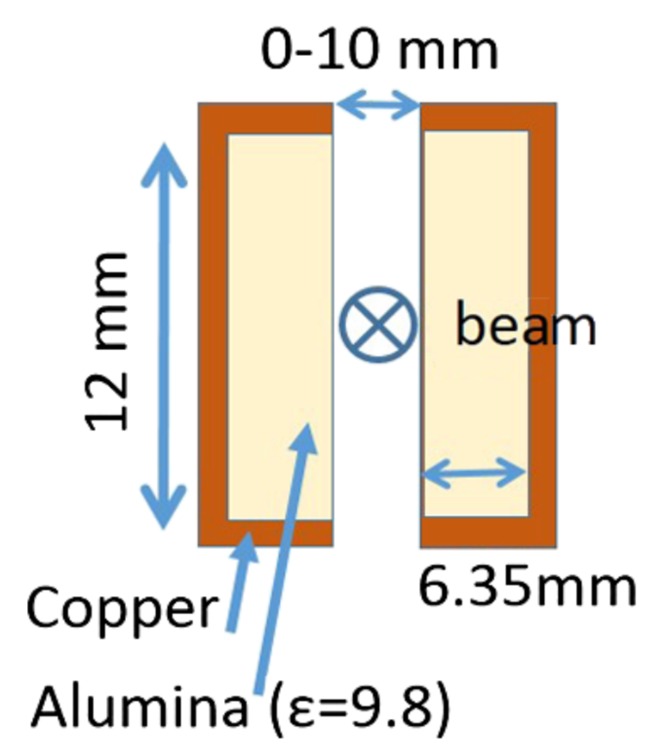


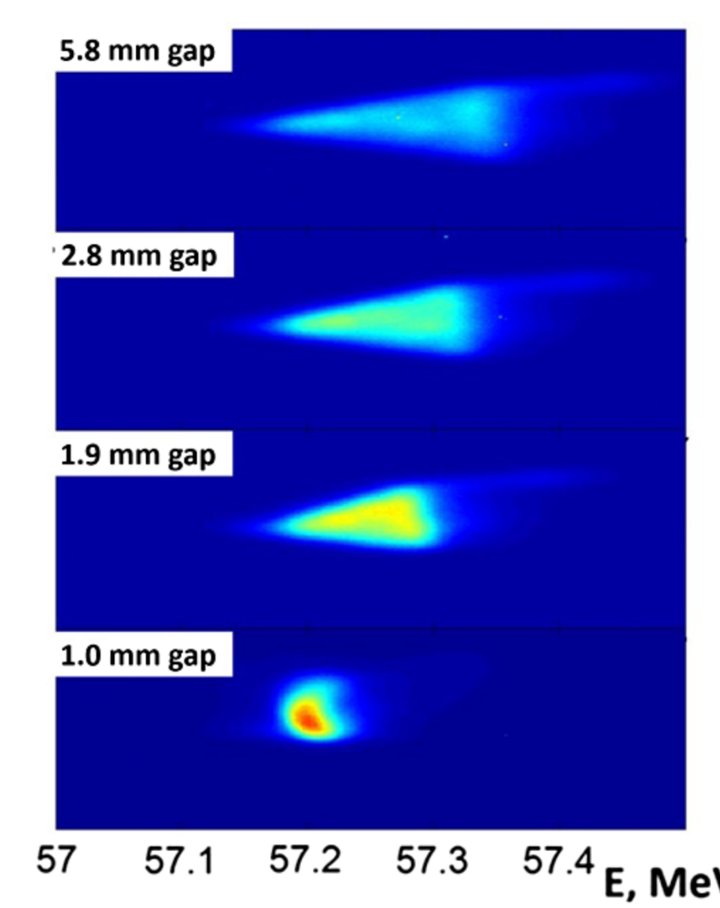


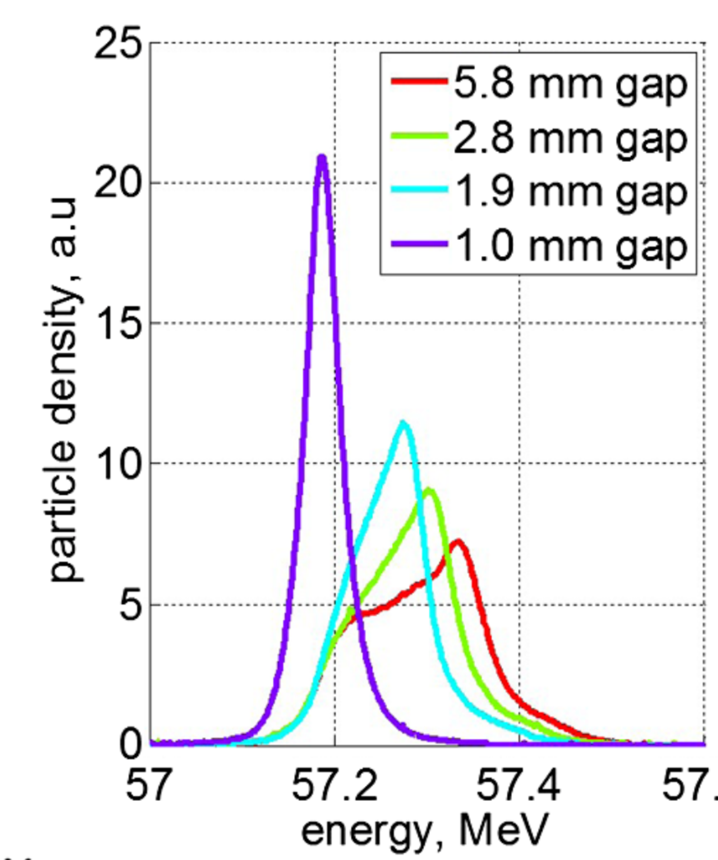
beam wakefields in the pipe are dechirping

- Chirp compensation by dielectric-based slab structure - S. Antipov *et al.*, Phys. Rev. Lett. 112, 114801 (2014)









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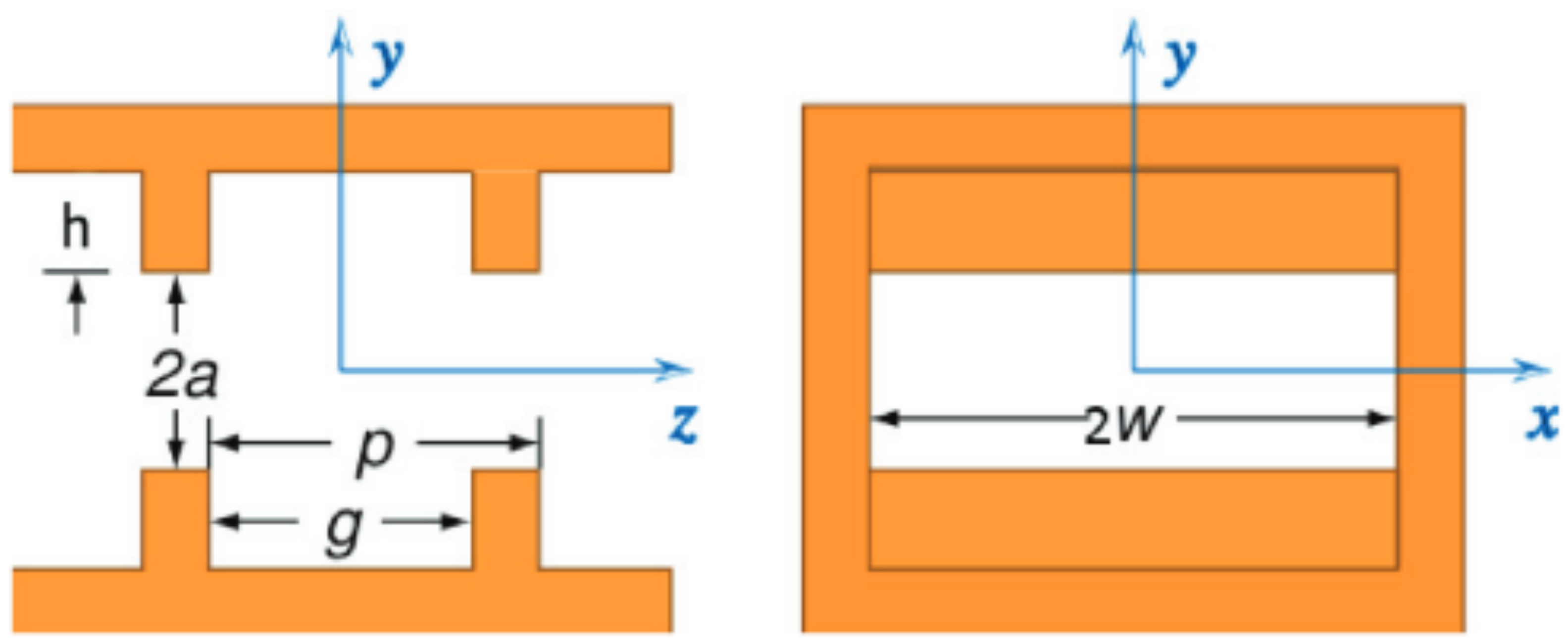
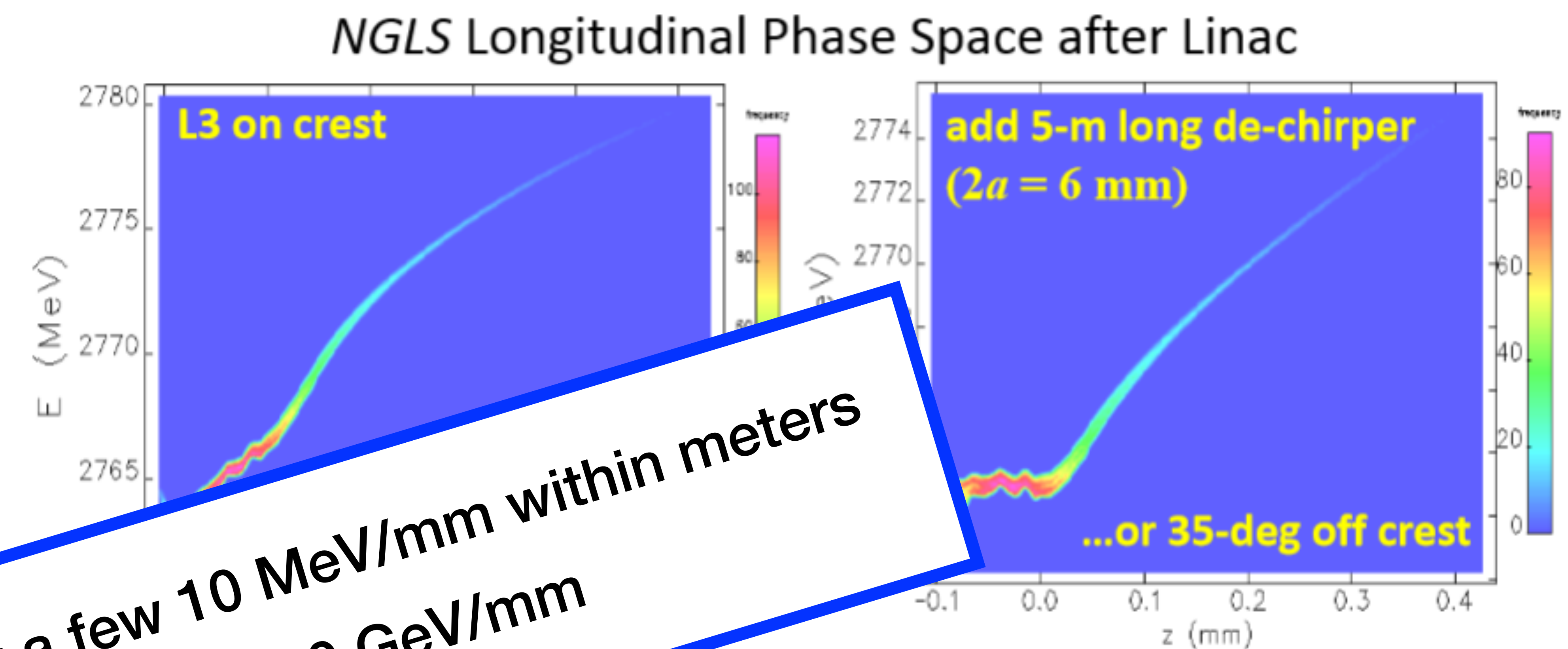
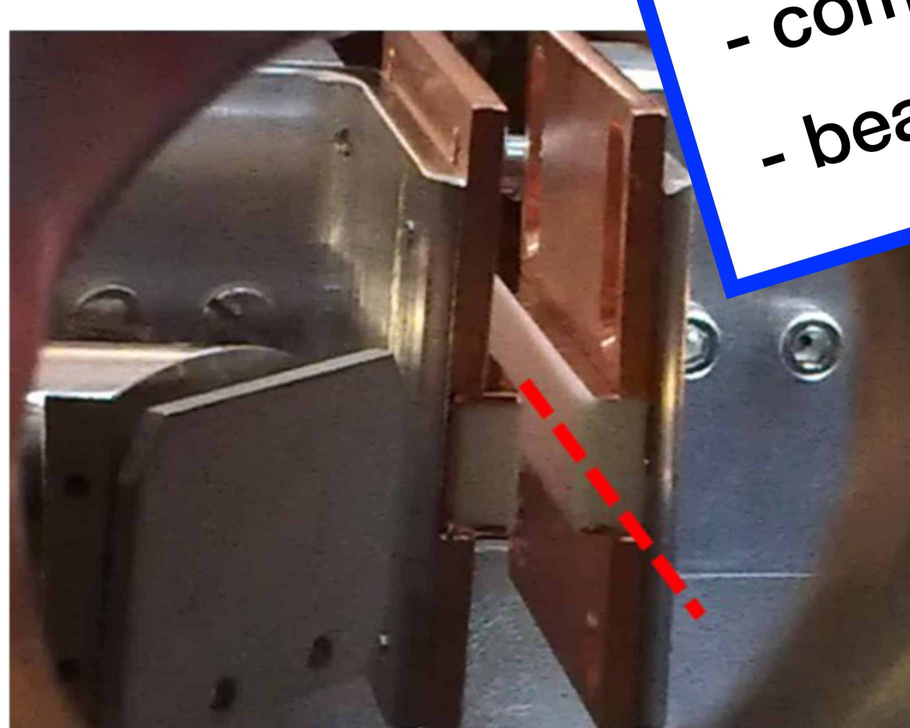


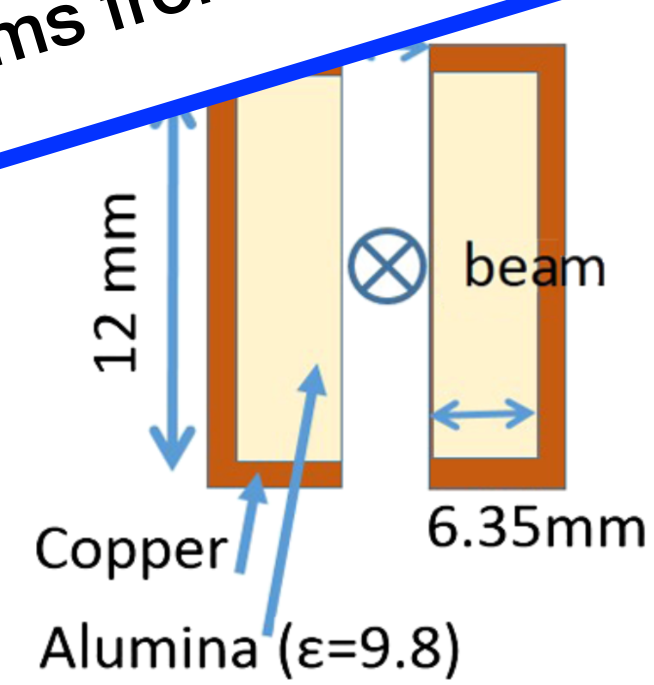


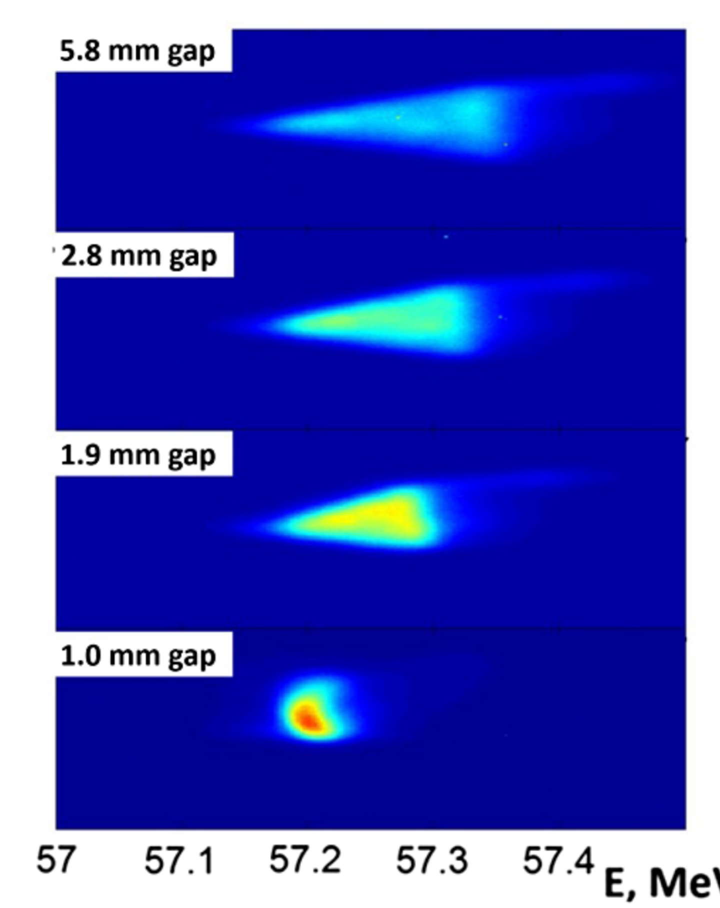
beam wakefields in the pipe are dechirping

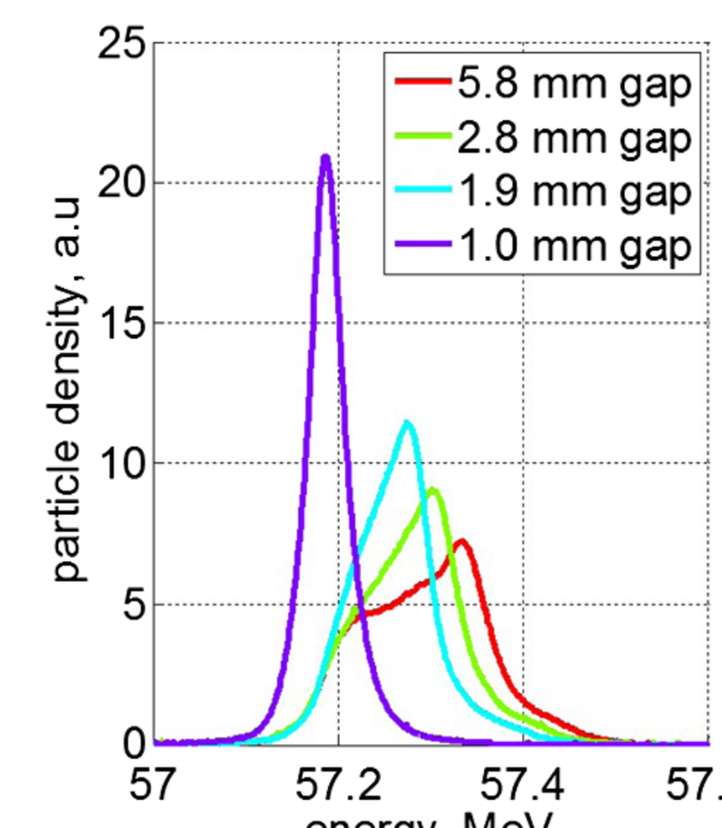
- compensate energy chirps at a few 10 MeV/mm within meters
- beams from plasmas feature chirps of 10 GeV/mm

> Chirp compensation by d... et al., Phys. Rev. Lett. 112, 114801 (2014)



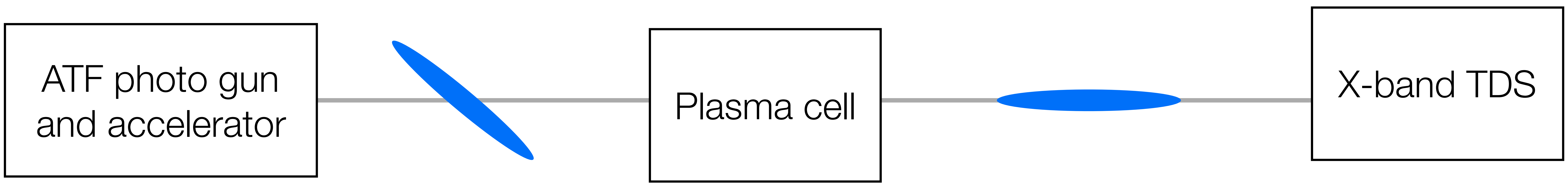






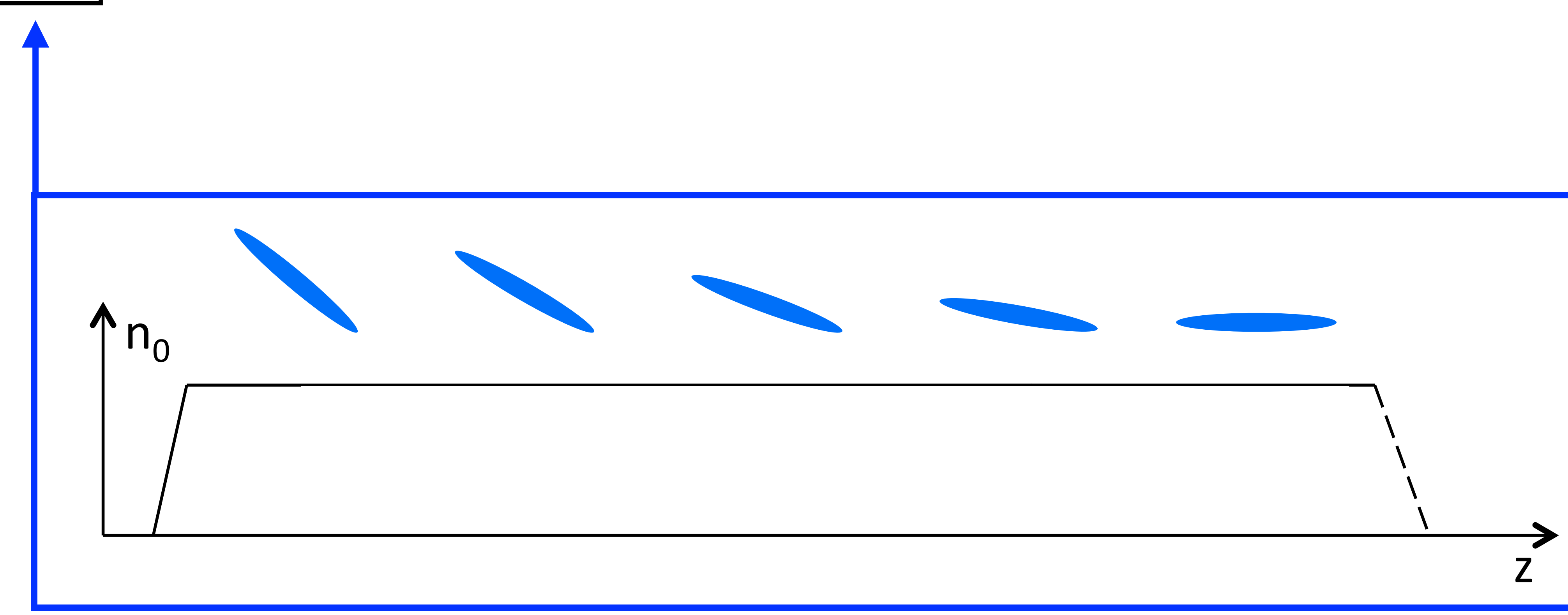
Energy-chirp compensation in plasma at ATF

Accepted experiment at ATF: utilise chirped electron beam to self-dechirp in a plasma wakefield

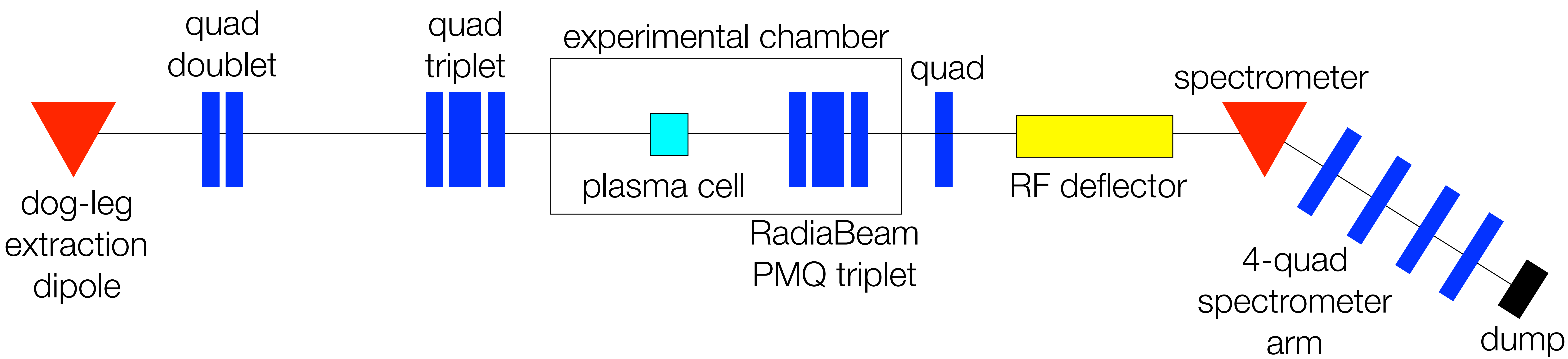


Electron beam requirements

- monotonically changing, increasing energy from head to tail
- an energy bandwidth of ≥ 1% rms
- sufficient current density to drive a wakefield
- rms bunch length short enough to fit inside 1/24th of a plasma wavelength



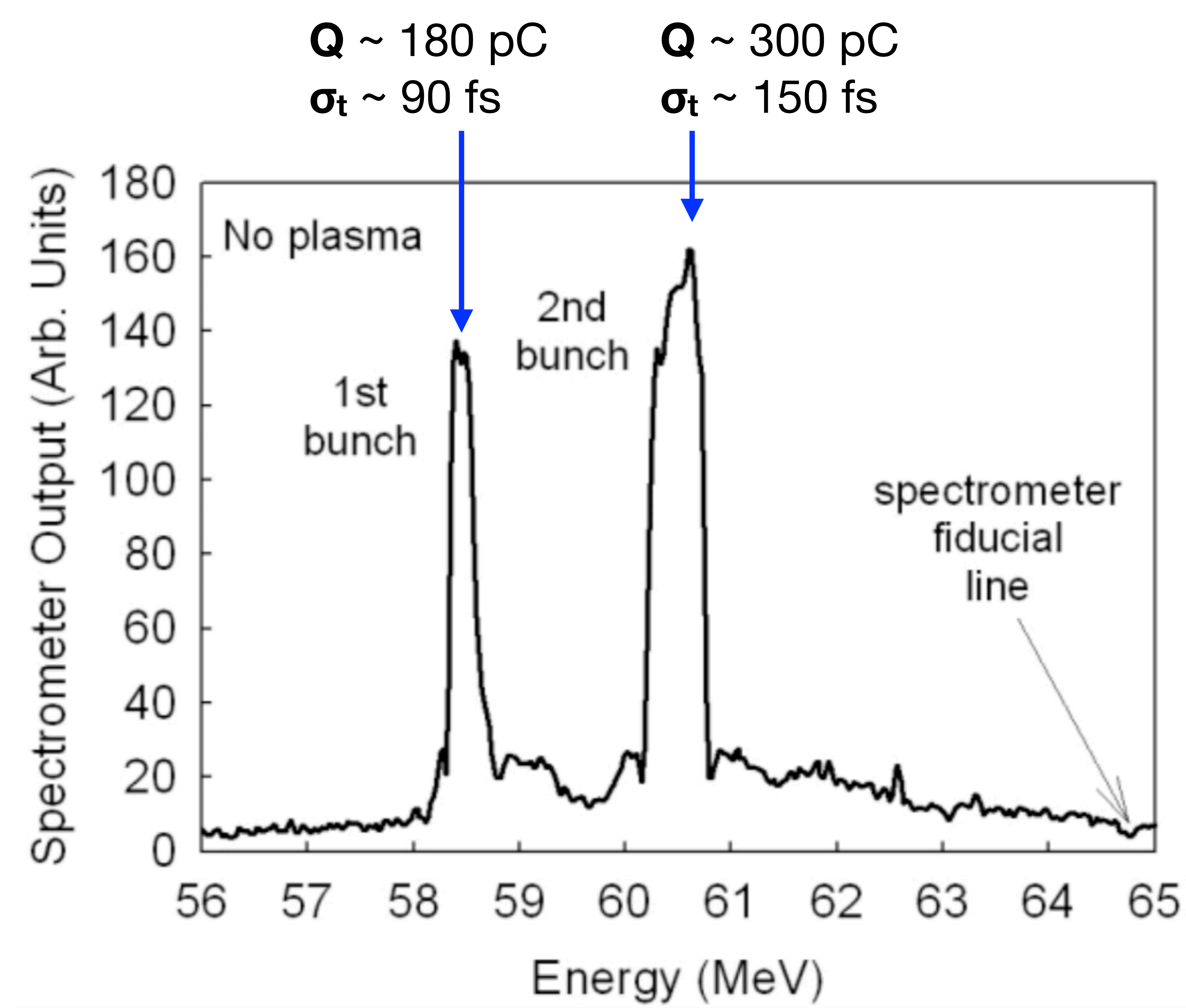
AE73 beam line configuration



- The optics of the ATF I-line were modified slightly for experimentation:
  - The plasma cell (designed, developed, and implemented by Sam Barber (LBNL)) and discharge setup were incorporated
  - A doublet and a triplet upstream of the plasma cell were incorporated for a tight focus at the plasma cell (to avoid severe emittance blow-up in the plasma cell)
  - A RadiaBeam permanent magnet quad triplet was installed in the experimental chamber to capture the heavily divergent beam upon exit of the plasma cell

Experimental determination of longitudinal working point

- The ATF gun has a bunch length of ~1 ps on-crest
- Need to find a regime where the bunch length is a lot shorter due to the plasma density requirements (σ_t = 140 fs for n_p = 10^{15} cm^{-3})
- Muggli *et al.* discovered a regime of bifurcation due to CSR breakdown occurring at large off-crest phases in the linac



P. Muggli *et al.*, Phys. Rev. Lett. **100**, 074802 (2008)
P. Muggli *et al.*, Proc. IPAC07, New Mexico, USA (2007)

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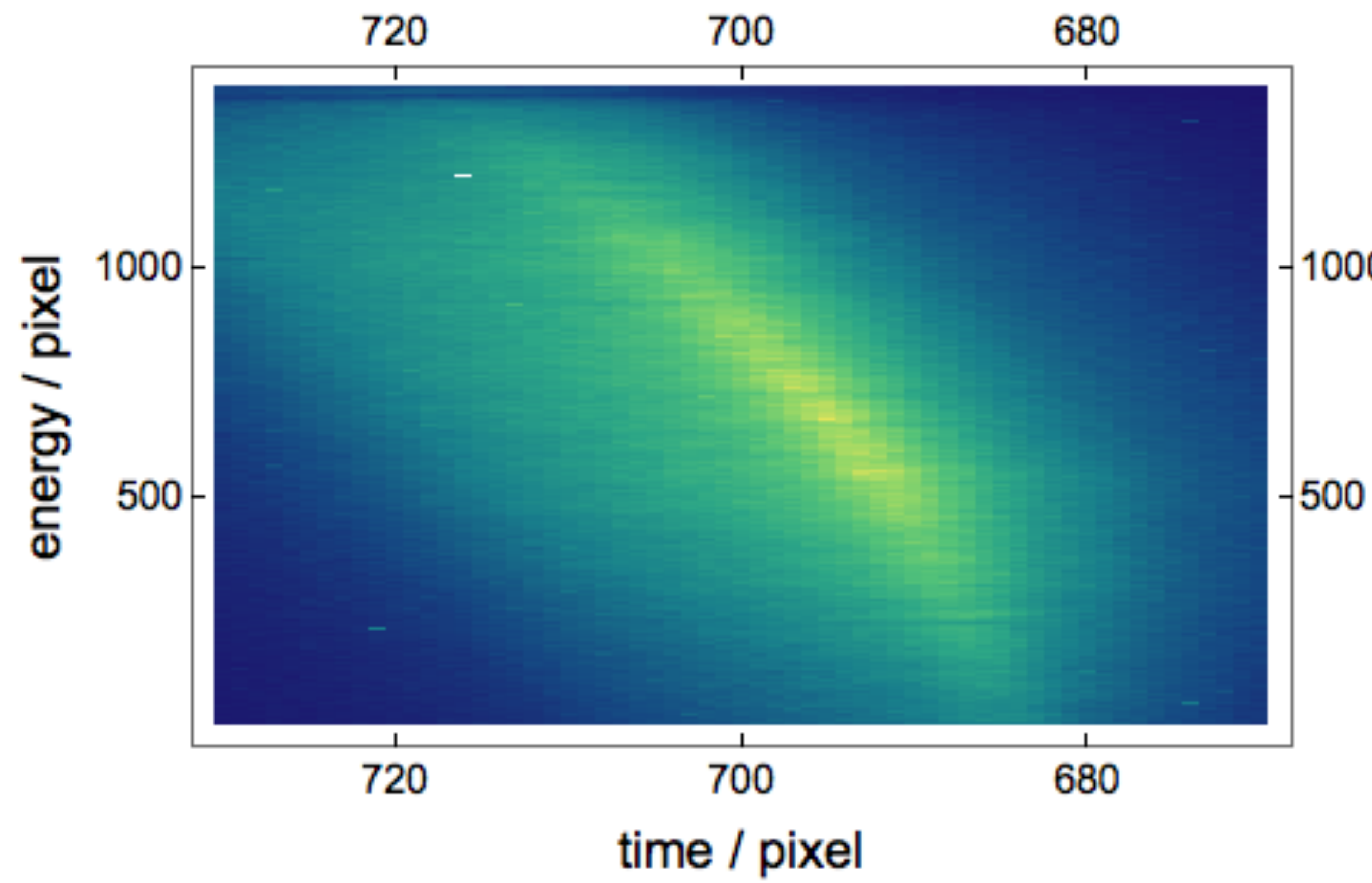
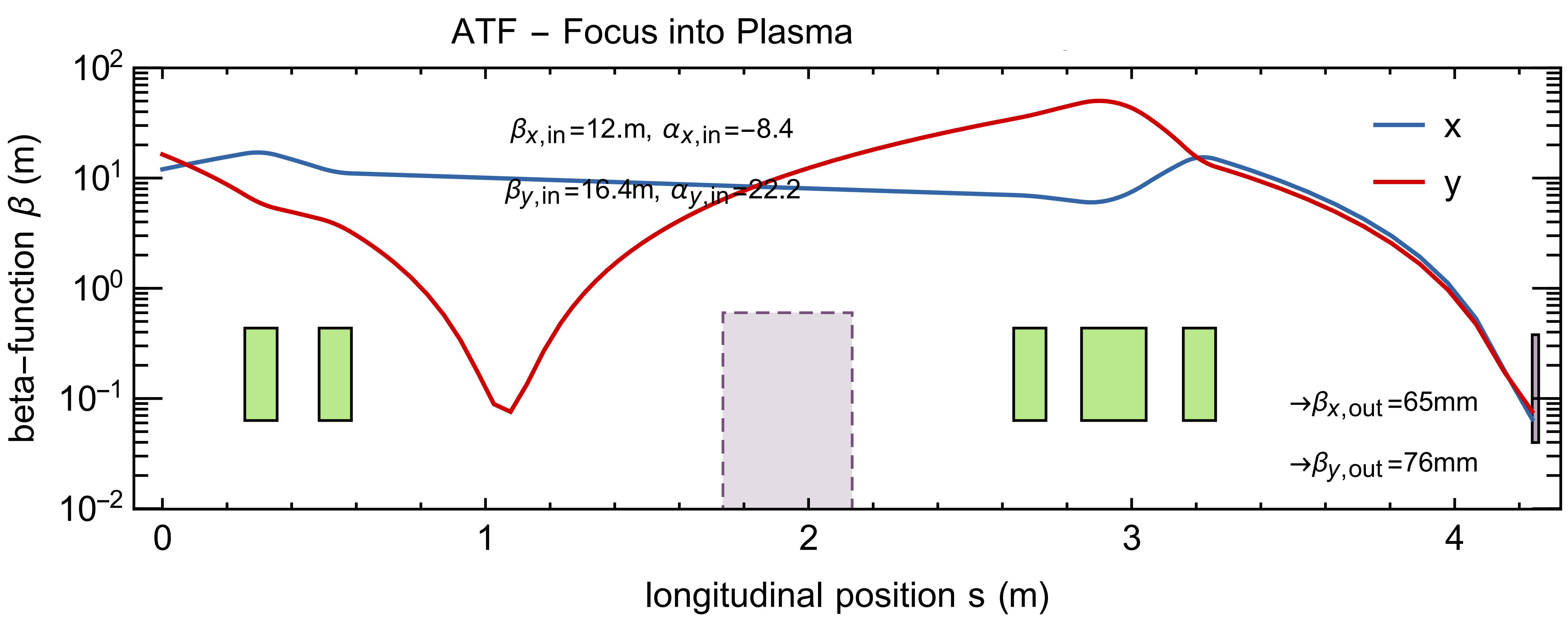
- Need to find a regime where the bunch length is a lot shorter due to the plasma density requirements (σ_t = 140 fs for $n_p = 10^{15}$ cm^{-3})
- Muggli et al. discovered a regime of bifurcation due to CSR breakdown occurring at large off-crest phases in the linac
- This state was recreated for us at ~12 deg off-crest, with the selection of one bunch using the high-energy slit in the dog-leg section
- The X-band RF deflector was used to image the longitudinal phase space of this higher energy bunch
- A rough time calibration (performed by hand, manually adjusting the X-band phase) and energy calibration (using the HES in the dog-leg, manually adjusting the dipole currents) gave bunch properties:

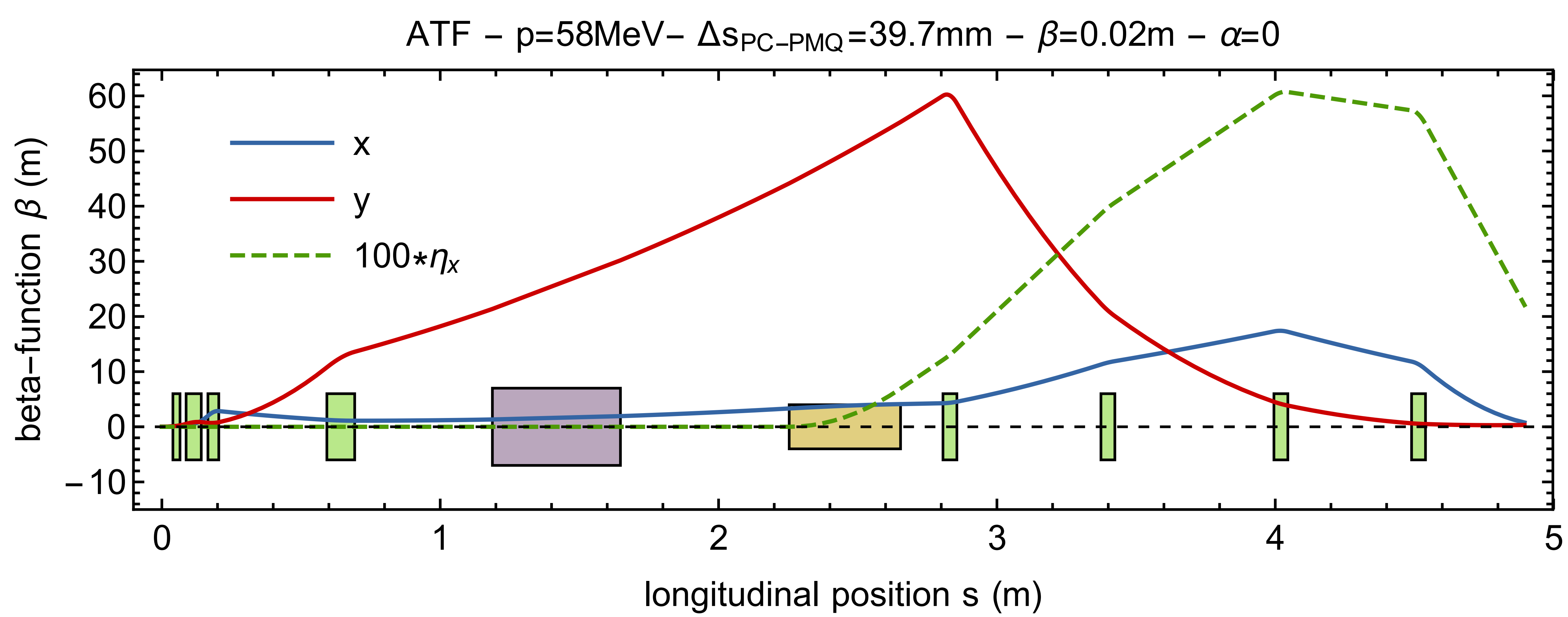


σ_t ~ 150 fs (45 μm)
Q ~ 200 pC
σ_δ ~ 1% (negative chirp)

→ consistent with Muggli *et al.*

Particle tracking of the ATF I-line in *elegant*





- The ATF I-line was simulated in *elegant*
- This was used to:
  - indicate the transverse beam size at the interaction point based on Twiss parameters derived from quad scans*,
  - suggest optics in the post-plasma beam line that would optimise the temporal and energy resolution at the X-band deflector

*consistent with Mikhail's experimental data

Expected dechirping effect from PIC simulations

<u>ATF bunch parameter range:</u>

$40 < \boldsymbol{\sigma_r} < 100$ μm*

$\boldsymbol{\varepsilon_n} = 2$ mm mrad

$50 < \mathbf{Q} < 200$ pC

$\boldsymbol{\sigma_t} \sim 150$ fs (45 μm)

$\mathbf{E} < 70$ MeV

$\boldsymbol{\sigma_\delta} \sim 1\%$ (negative chirp)

$\mathbf{n_b} \sim 5\text{x}10^{14}$

<u>ATF plasma parameter range:</u>

$10^{14} < \mathbf{n_p} < 10^{15}$

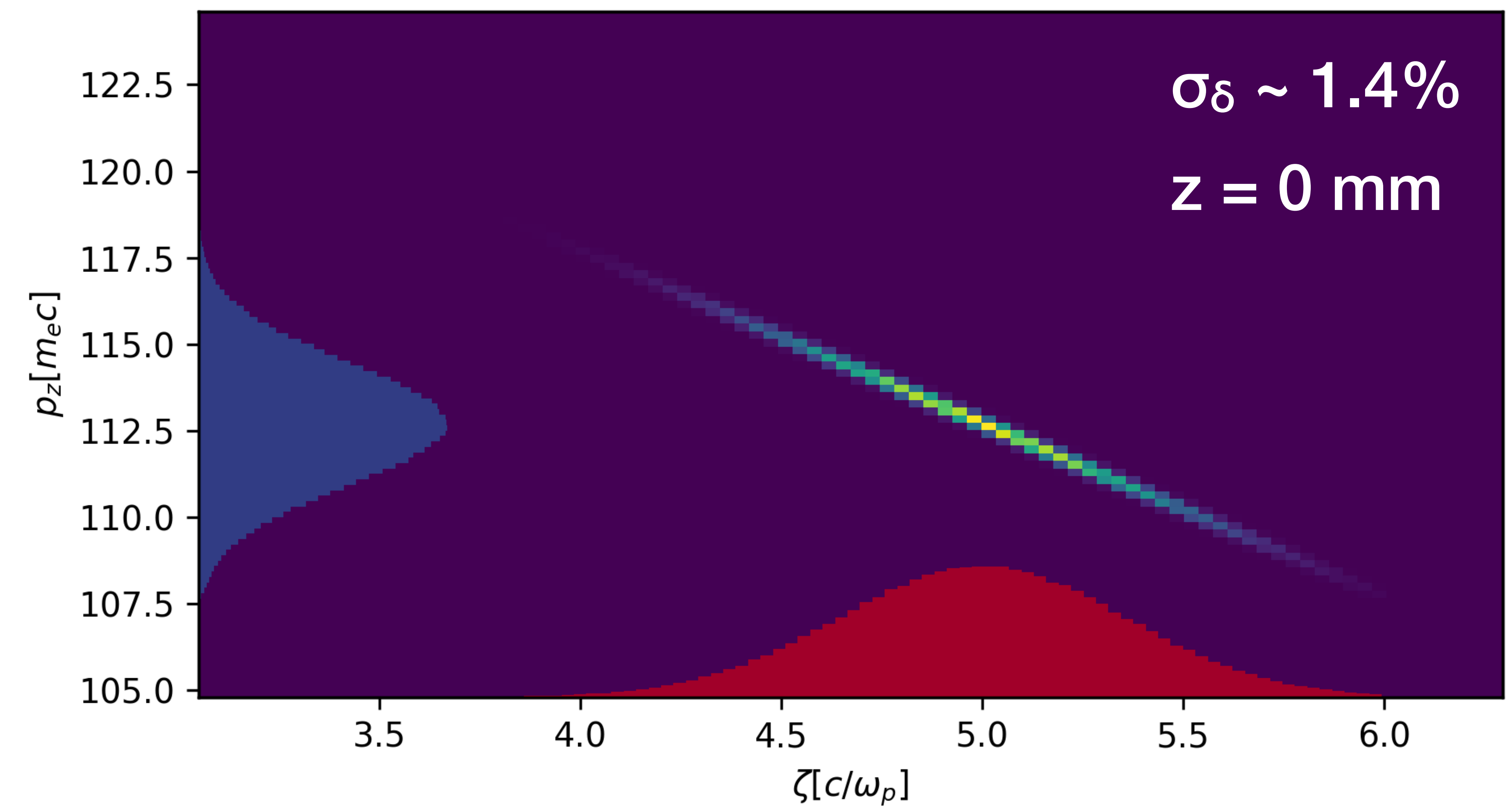
$\mathbf{L} = 20$ mm

*the transverse beam size was experimentally determined by Mikhail

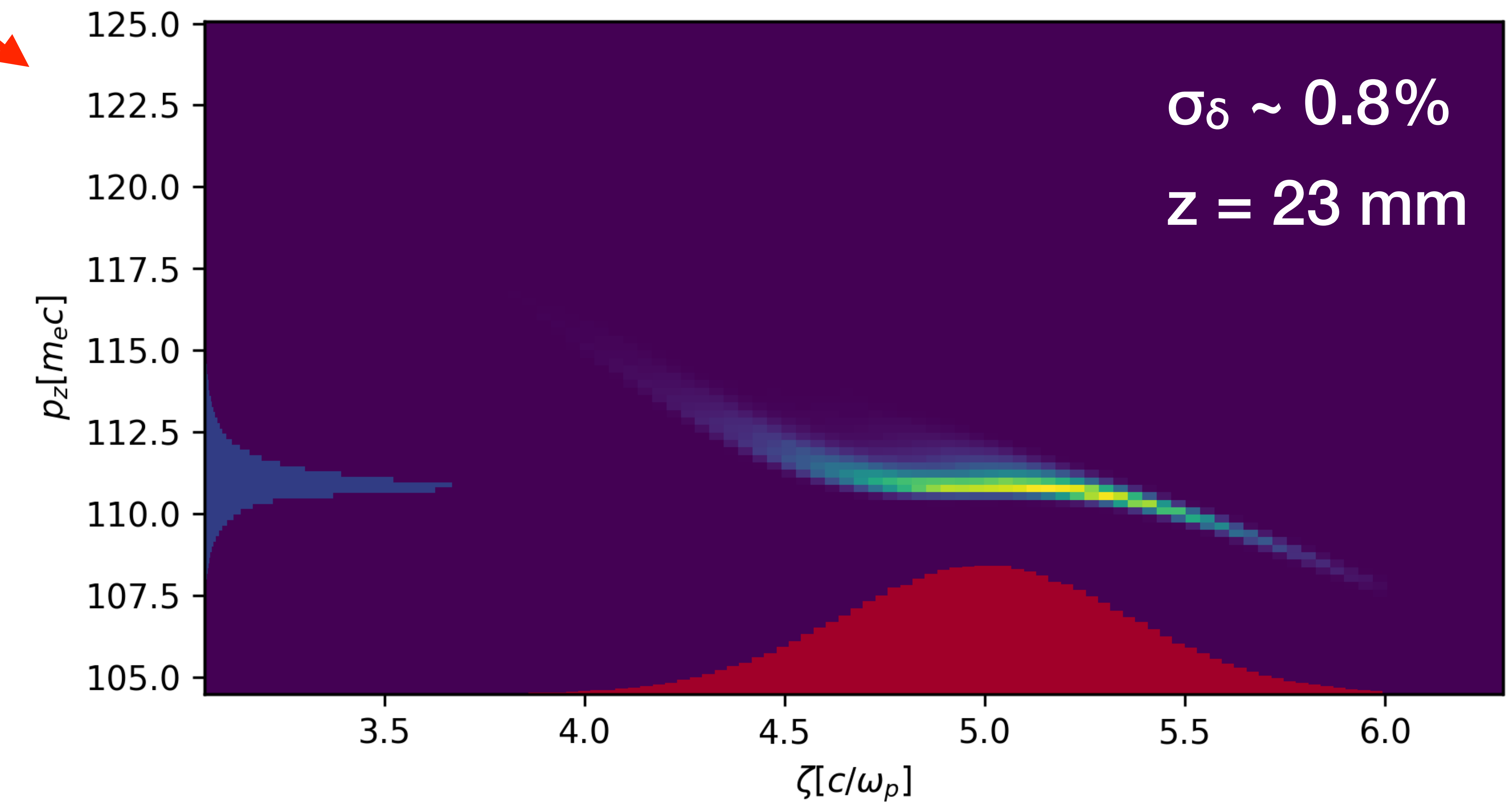
Expected dechirping effect from PIC simulations

Simulated bunch parameters:
σ_r = 40 μm
ε_n = 2 mm mrad
Q = 150 pC
σ_t = 150 fs (45 μm)
E = 58 MeV
σ_δ = 1% (negative chirp)
n_b = 5×10^{14}

Simulated plasma parameters:
n_p = 10^{15} cm^{-3}
L = 20 mm

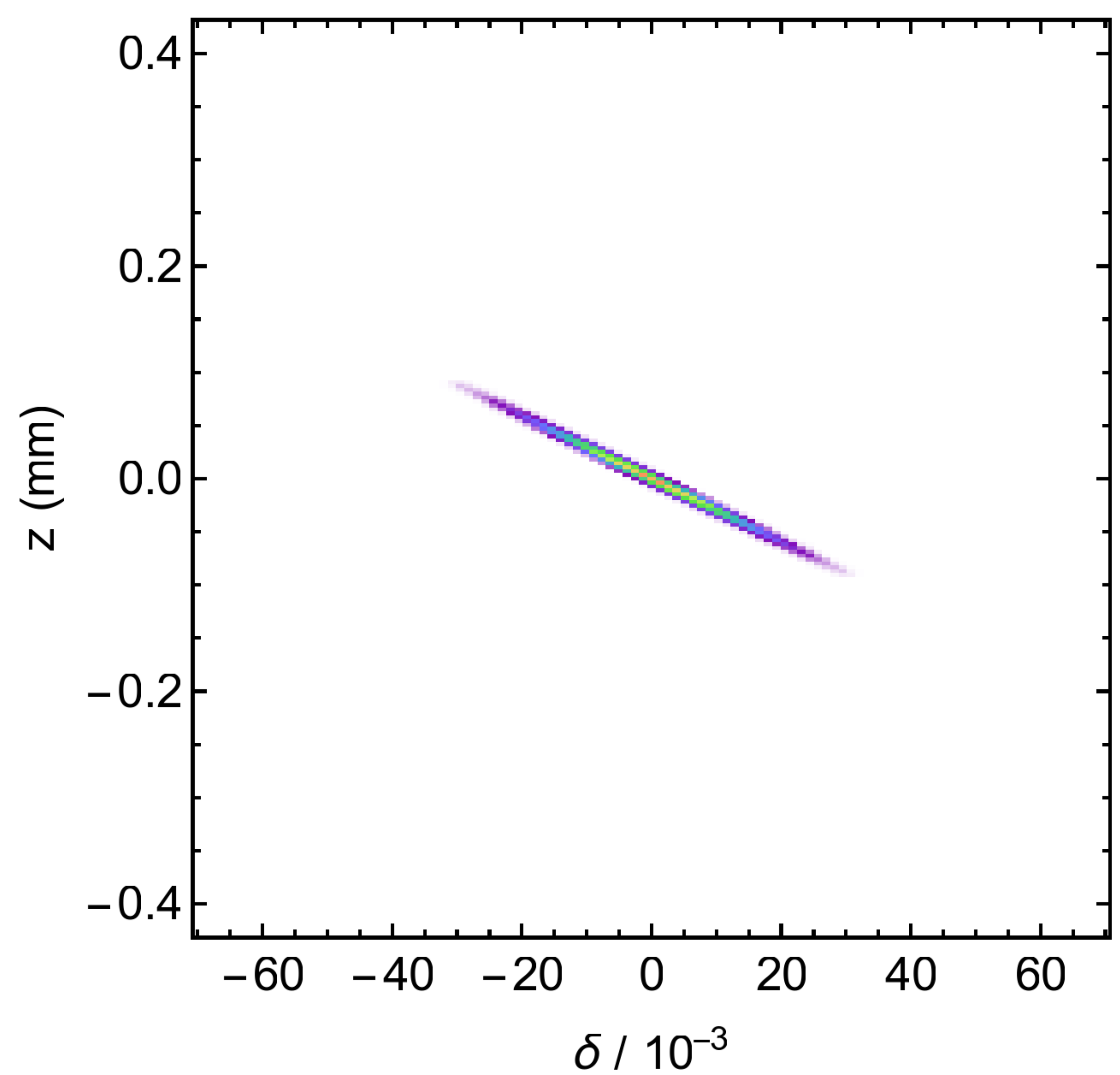


dechirping effect

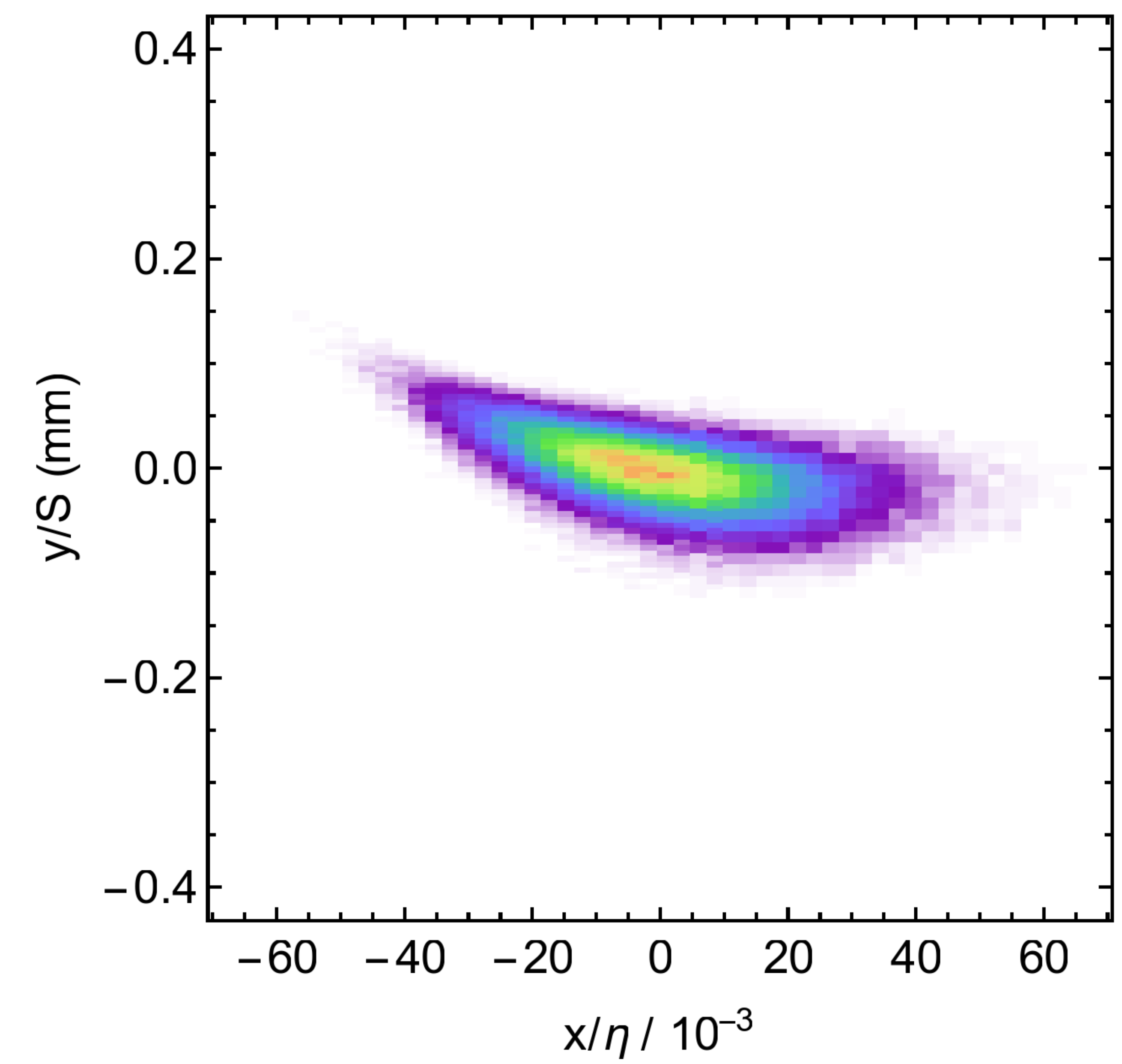


Comparison of ‘true’ to ‘measured’ long. phase space

Longitudinal profile of the dechirped bunch at the exit of the plasma cell

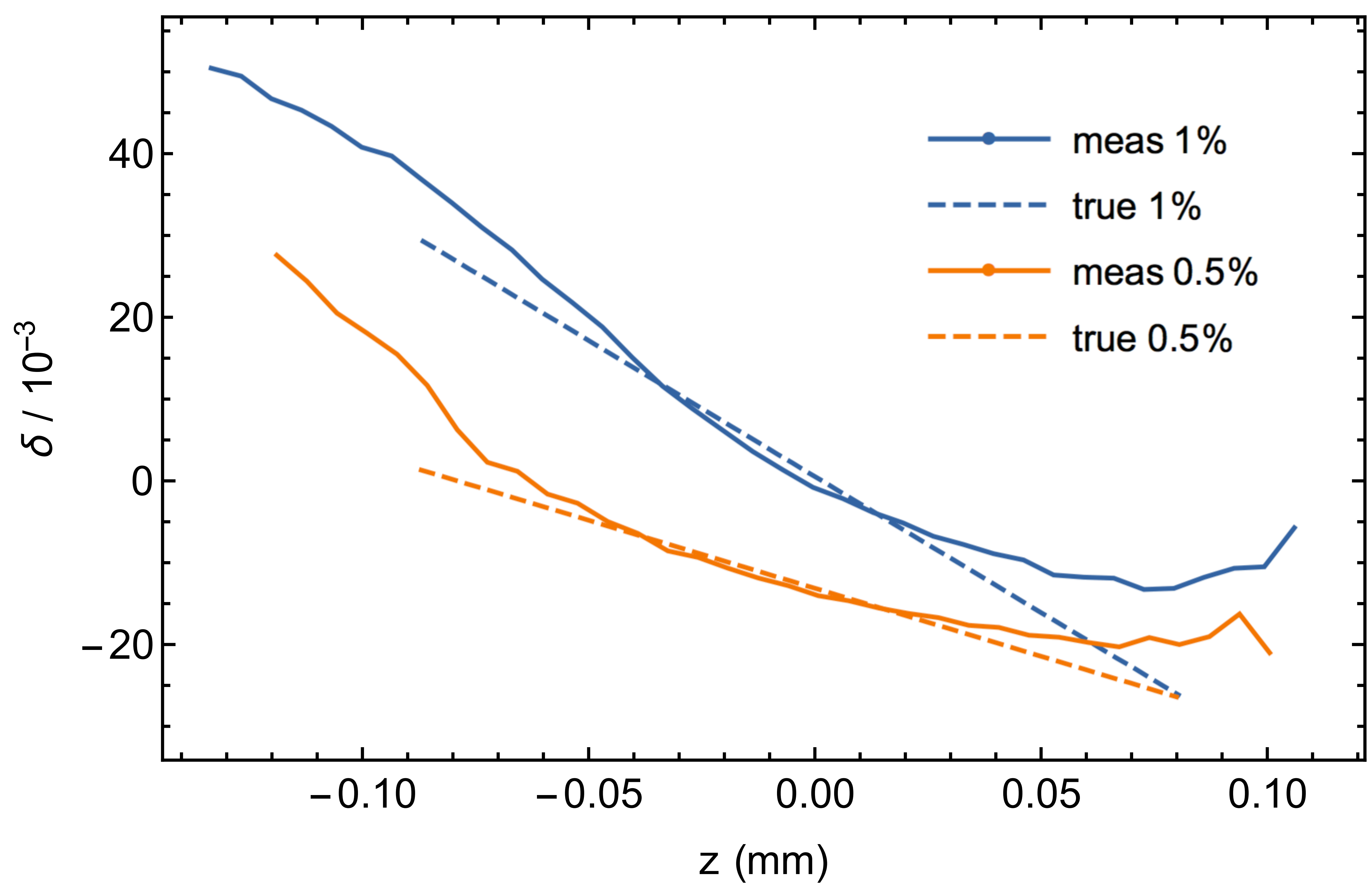


Reconstructed longitudinal profile of the dechirped bunch on the spectrometer screen



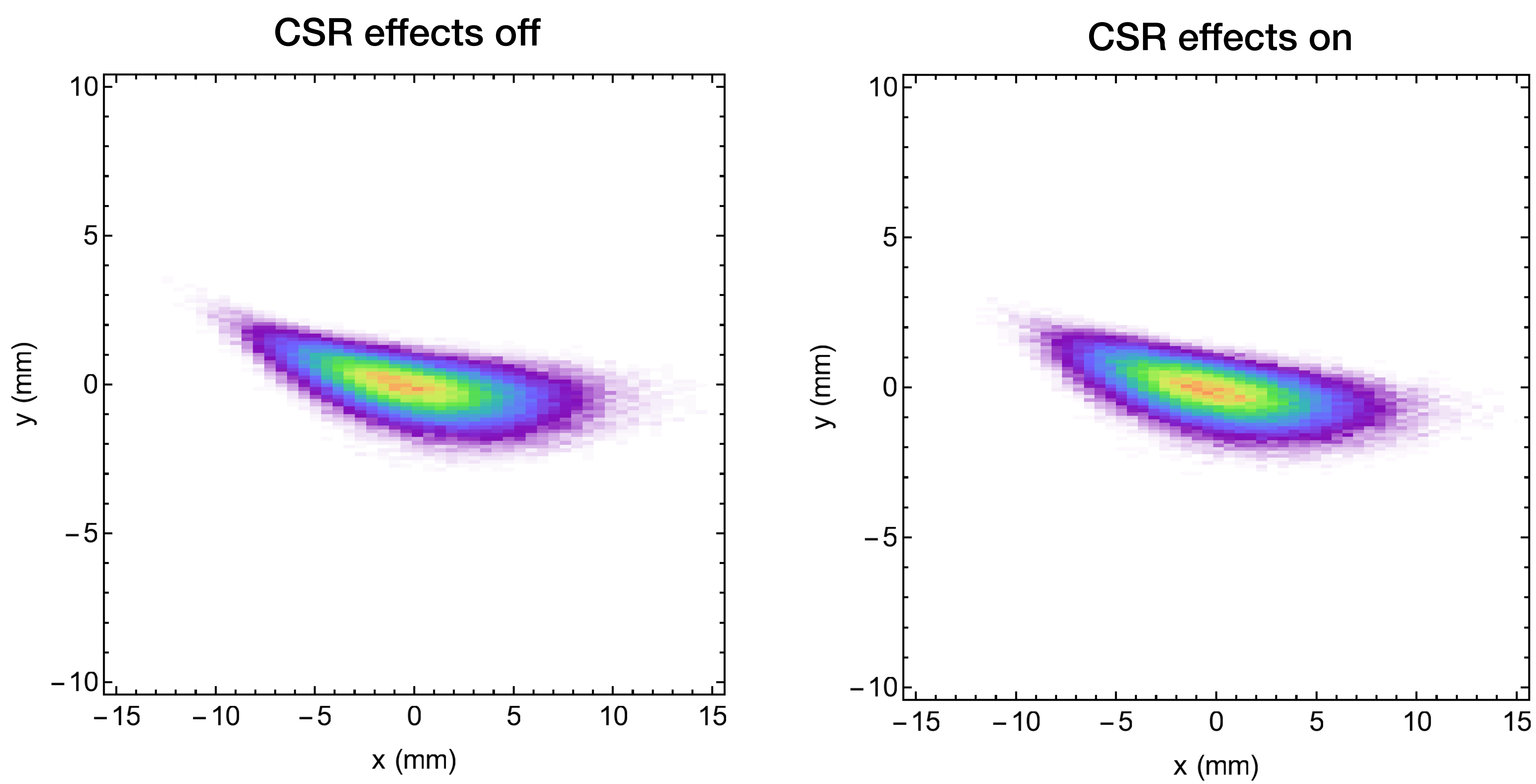
- The spectrometer screen is normalised by the RF deflector streak and the dispersion from the dipole to give a representation of the longitudinal phase space
- The reconstructed profile is different to the longitudinal profile at the exit of the plasma due to a chirp and energy spread imparted on the bunch by the RF deflector

Reconstruction of 0.5% dechirping effect



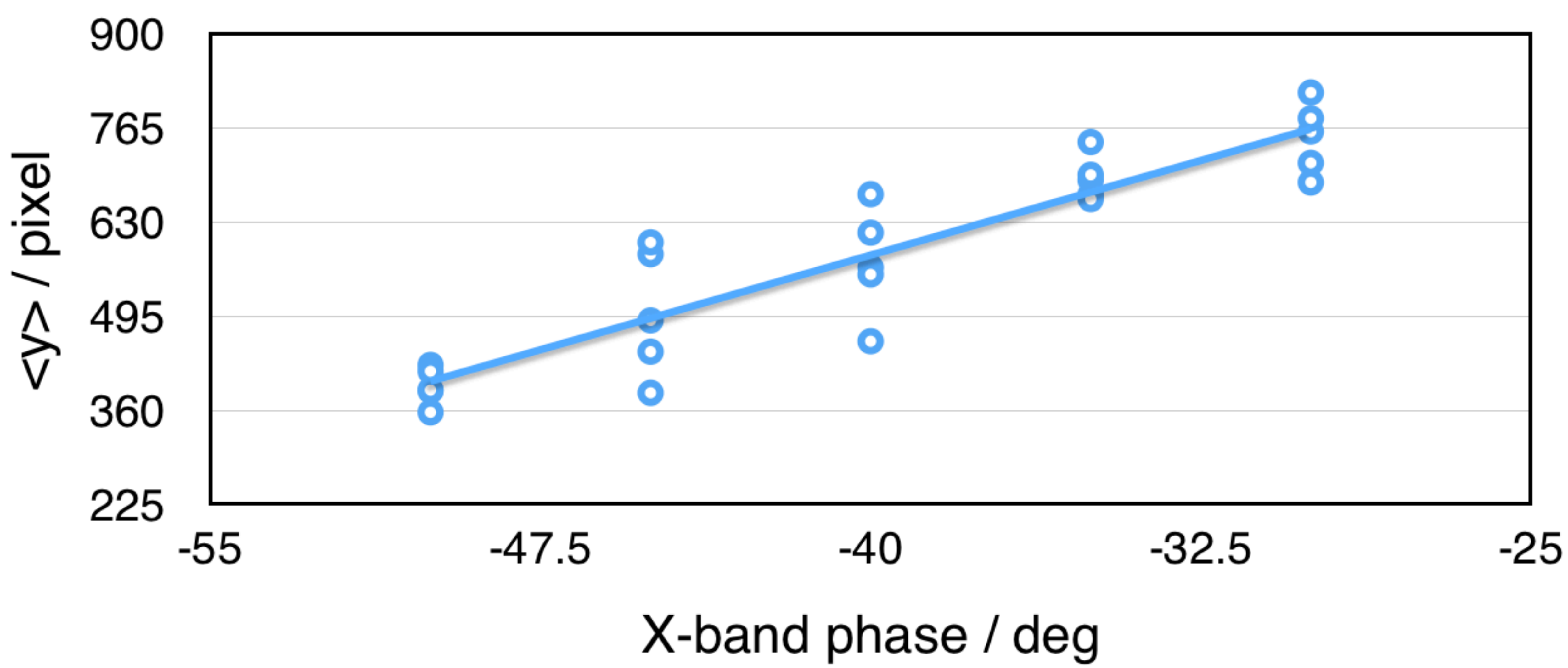
- The reconstructed longitudinal slice centroids for the dechirped bunch (σ_δ = 0.5%) compared to a reconstruction of the un-dechirped bunch (σ_δ = 1%)
- The reconstructed bunches are discernible, however, this is for idealised beams

Expected CSR effects from the spectrometer dipole



- CSR effects from the spectrometer arm appear to be negligible, however:
  - fluctuations in shot-to-shot bunch charge caused by jitter on the high energy slit are not taken into account
  - elegant assumes a pencil-like beam for CSR calculations, which is not valid in this case
- It is essential to experimentally quantify CSR effects in order to disentangle from a sub-percentage dechirping effect

Time calibration of the X-band RF deflector



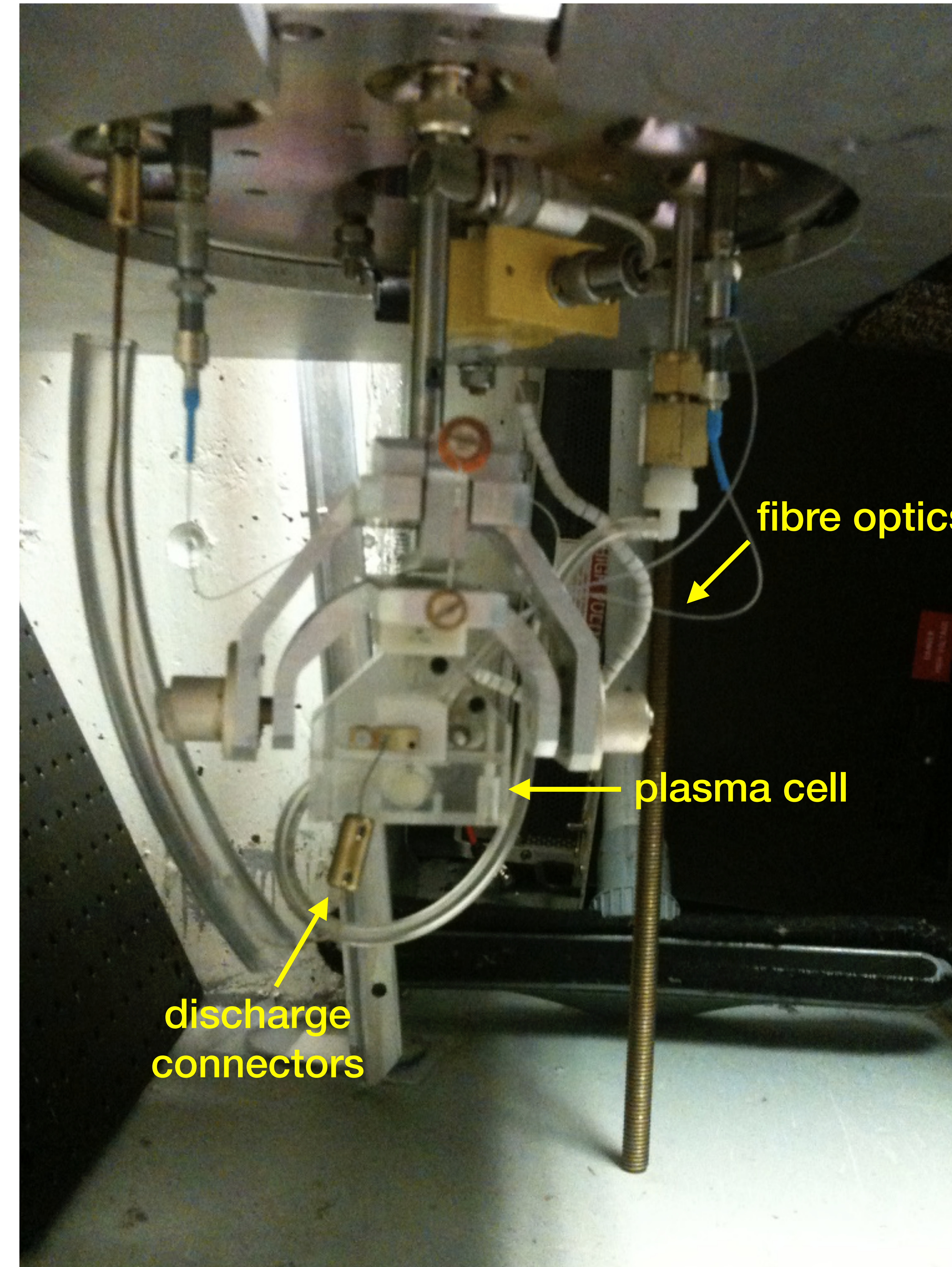
S = 1.04 µm/fs

R_t = 105 fs

- Due to the X-band RF deflector’s temporal resolution being defined, in part, by the R_{34} matrix element it was necessary to re-calibrate every time the optics were changed
- An automated script was written for this purpose in order to speed up experimentation
- In the example above the optics were not optimised, nor was the full power used in order to avoid large induced energy spread
- However, with optimised optics and full power it is expected that the temporal resolution could be as low as > 0.1 fs

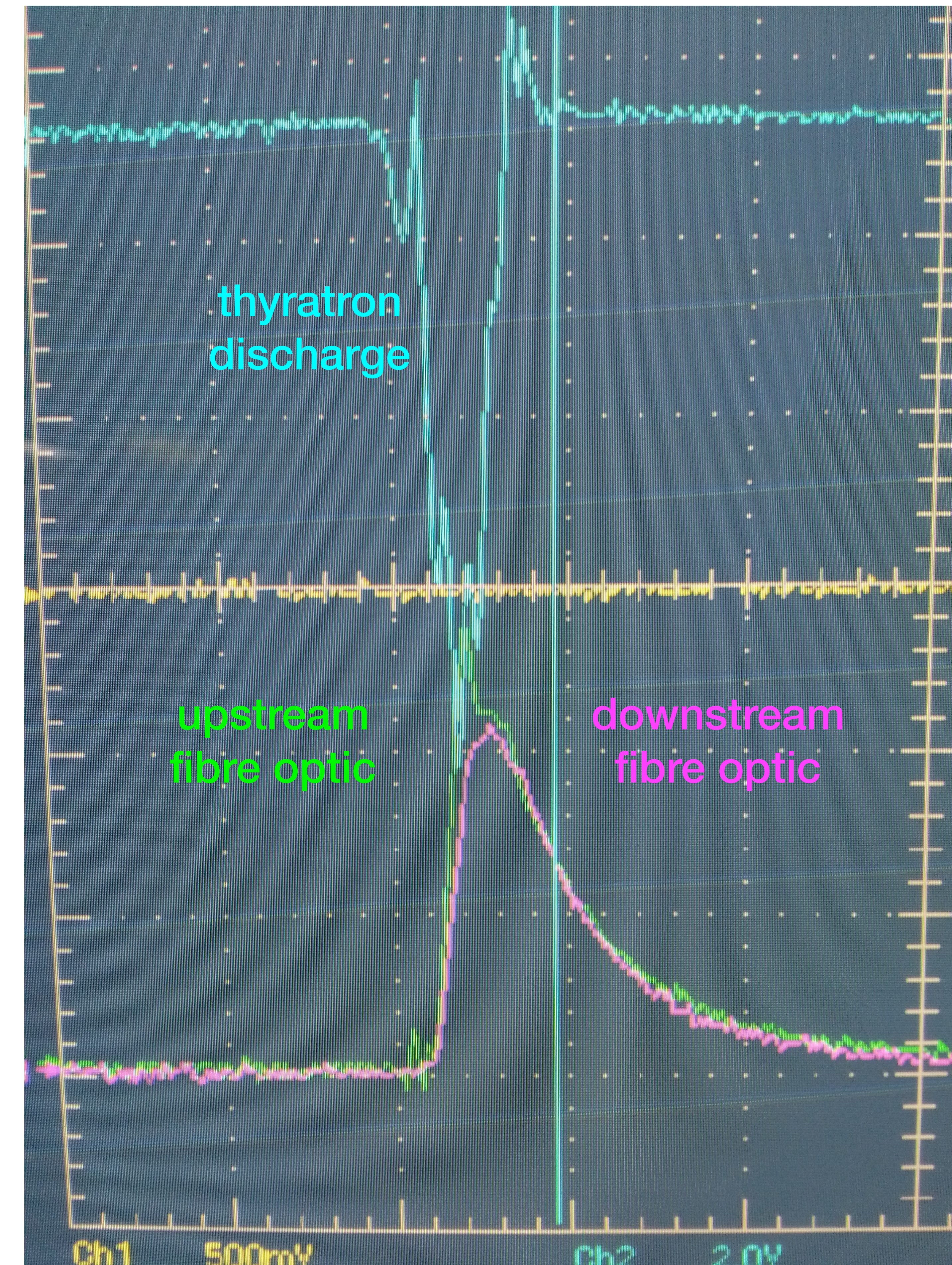
Successful creation of a uniform plasma

- The 20 mm long plasma cell with capillary discharge capability was resurrected from its last use (for Sam Barber's thesis studies, 2015)
- The thyratron discharge unit proved to be the most difficult aspect to



Successful creation of a uniform plasma

- The 20 mm long plasma cell with capillary discharge capability was resurrected from its last use (for Sam Barber's thesis studies, 2015)
- The thyratron discharge unit proved to be the most difficult aspect to
- Once the thyratron was operational, the light output from fibre optics cables at both ends of the plasma cell demonstrated uniform plasma generation
- Mathematica scripts were then used to modify the discharge time such that the electron bunch arrival time coincided with varying plasma densities*



*the spectrometer was not connected to the fibre optics so analysis of the hydrogen Balmer lines, and thus a plasma density measurement, was not possible during the last beam time

Future plans

- Perform density measurements of the plasma using Stark broadening of the H_α Balmer line
- Reassess the CSR breakdown state with the new klystrons and characterise both bunches, comparing to previous data and that of Muggli *et al.*
- Characterise CSR effects (to determine the max. bunch charge with which we can operate) by manipulating the image on the spectrometer screen with the mask and observing the effect on the spectrometer screen
- High statistic measurements at IPOP8 (the screen immediately downstream of the RF deflector) of bunches injected into plasma, with both the RF deflector on and off, to quantify the fluctuation in Twiss parameters upon exit of the plasma
- Perform coarse plasma scans in steps of half an order of magnitude between 10^{14}-10^{17} cm^{-3} with mid-level stats to compare longitudinal phase space distributions with PIC simulations for those bunch parameters
    - Does self-modulation occur?
- Repeat with plasma densities in the range 10^{14}-10^{15} cm^{-3} i.e. where $6\sigma_z < \lambda_p/4$
- Repeat the above point with high statistics for the optimal de-chirping density, suggested by experimental data, with the data-taking protocol being a screen grab at:
    - IPOP8 with the RF deflector on
    - The spectrometer screen with the RF deflector off
    - The spectrometer screen with the RF deflector on

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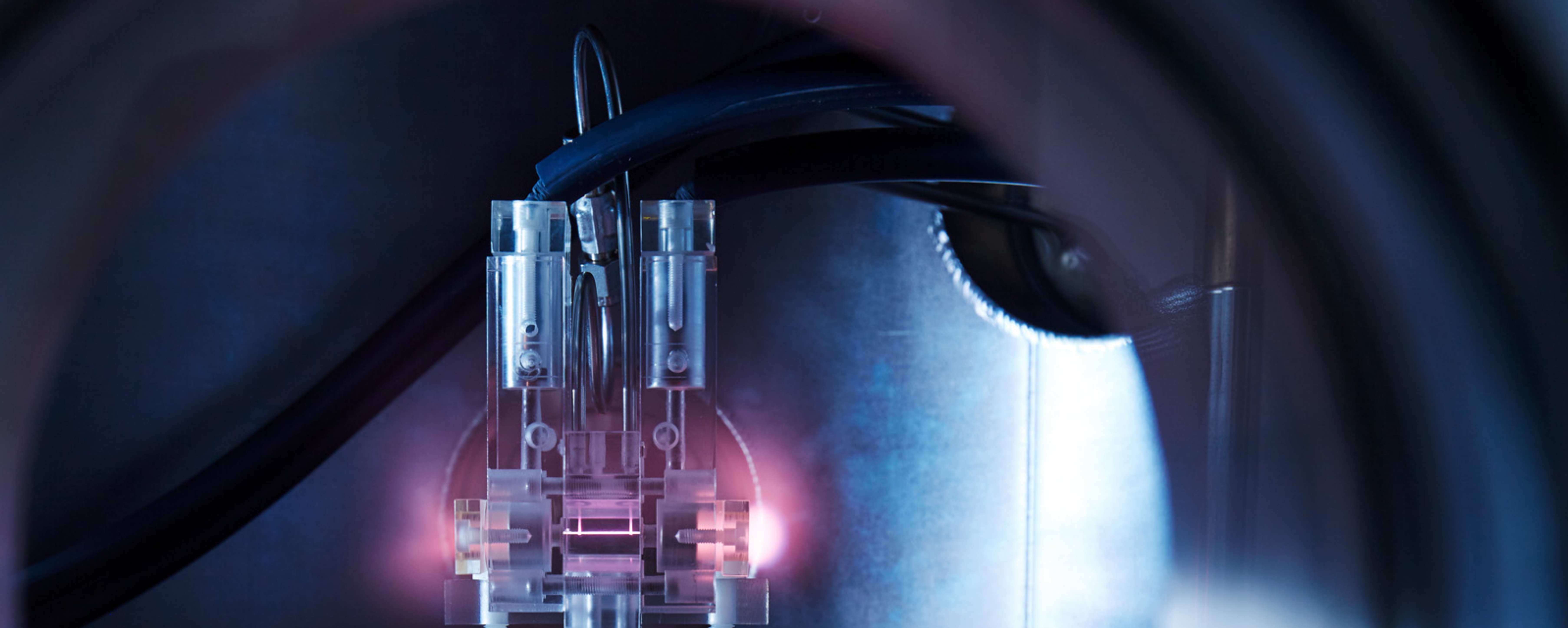
Summary



- The AE73 beam line configuration has been modelled and explored in *elegant*
- With the help of these simulations and hours of experimental data taking by Mikhail and Christina an experimental working point has been found
- The X-band RF deflector has been debugged and calibrated (optics still require optimisation)
- A plasma cell from previous experimentation has been revived with a new thyratron and has been shown to be operational
- Experimentation is ready to resume in Jan 2018 with the new linac and gun klystrons providing stable electron beams for dechirping

2018 Experiment Time Estimates

Run Hours (include setup time in hours estimate): 100
Number of electron beam only hours: 100
Number of CO_2 laser hours delivered to laser experiment hall (”FEL room”): 0
Number of CO_2 laser hours, + ebeam, delivered to electron beam experiment hall: 0

Overall % setup time: 50%

Hazards & installation requirements:
Large installation (chamber, insertion device etc…): N
Laser use (other than CO_2): N
Cryogens: N
Introducing new magnetic elements: N
Introducing new materials into the beam path: N
Any other foreseeable beam line modifications: N

Electron Beam Requirements

Parameter	Nominal	Requested Experiment Parameters
Beam Energy (MeV)	50-65	65
Bunch Charge (nC)	0.1-0.5	0.2
Compression	Down to 100 fs (up to 1 kA peak current)	100 fs
Transverse size at IP (sigma, um)	30 – 100 (dependent on IP position)	40um
Normalized Emittance (um)	1 (at 0.3 nC)	1
Rep. Rate (Hz)	1.5	1.5
Trains mode	Single bunch	single

Special Equipment:
Deflecting cavity